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Life cycle assessment of a biobased chainsaw oil made on the farm in Wallonia

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Abstract
Purpose The environmental issue is a particular concern for chainsaw oils because these fluids represent a total loss system. The aim of this study is to quantify the environmental impacts of a biobased chainsaw oil made on the farm in Wallonia (a region of Belgium) and to compare it with a model mineral chainsaw oil. With this study, the aim is also to participate in the development of the life cycle assessment (LCA) methodology applied to the biolubricant sector since LCAs on these products are quite limited and rarely sufficiently detailed.
Method In this LCA, the attributional approach is applied. Seven impact categories are studied. The methods for life cycle impact assessment are IPCC, ReCiPe, CML and USEtox. The functional unit is 1 kg of base oil. Seven sensitivity analyses are performed.
Results and discussion Results indicate that the biobased chainsaw oil made on the farm has a lower impact for the global warming potential, the abiotic depletion potential, the ozone depletion potential and the photochemical oxidation potential. On the contrary, it has larger acidification, aquatic eutrophication and aquatic ecotoxicity potential impacts. Regarding the contribution of the life cycle stages of the biobased chainsaw oil, the agricultural stage causes the highest contribution in all impact categories. For the mineral chainsaw oil, the refining stage is preponderant for all impact categories except for the global warming potential for which the end-of-life stage contributes the most. When taking additives into account, conclusions regarding the comparison between the oils are not reversed. Even if it was necessary to consume more biobased than mineral chainsaw oil, conclusions regarding the comparison of the oils would not be reversed. In the same way, a different allocation procedure for rapeseed oil and rape meal, a different rape seeds yield or different extraction yields in the refining stage of the mineral base oil do not change the results of the comparison. For the biobased chainsaw oil, the substitution of only one active substance in the agricultural stage could result in an important decrease of the freshwater ecotoxicity impact.
Conclusions The biobased chainsaw oil has a lower impact in four out of the seven impact categories and a higher impact in three impact categories. By providing a detailed LCA on a biobased chainsaw oil, this study contributes to the development of LCA applied to biobased lubricants.

Keywords Biobased · Chainsaw oil · Comparative LCA · Lubricant · Mineral · Rapeseed oil

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1 Introduction

Most of the products that are consumed today are connected with the petrochemical industry. Reducing dependency on oil while at the same time developing sustainable alternatives is therefore indispensable.

In the chemical and material industries, biomass is today the main widely available substitute for fossil carbon, and so

the development of biobased products[1] has become a major issue. But to fit in full transparency into this transition towards a post-petroleum society, biobased products need to demonstrate they are sustainable. Regarding the environmental aspect, there is therefore an increasing need to describe and quantify the potential impacts of these products. In this context, environmental evaluation through life cycle assessment has become fundamental (European Commission 2008).

Within the biobased products sector, biolubricants are one of the product groups which are today most advanced in terms of technological development and market knowledge. While the total European lubricant market is slightly decreasing over the years, a different tendency is seen for biolubricants (Luther 2010). Some market studies (Frost & Sullivan 2007) forecast a continuously growing market of this product group. There may be a number of reasons for this. First, there is an underlying trend in Europe to favour less polluting and less dangerous products. This trend is found in different regulations and directives (REACH, Directive 2004/35/EC on environmental liability, Directive 98/8/EC on biocidal products). On the lubricant formulators' side, there is also a willingness to find alternative raw materials in order to have more flexibility and to disconnect from oil price. Finally, vegetable-based lubricants have a number of advantages, not only from the environmental side (biodegradability, low toxicity, renewability) but also from the technical side (performance similar to or better than conventional petroleum fluids, Miller 2009). However, as for other biobased products, life cycle assessments on these products are very limited (Wightman et al. 1999a, b; Våg et al. 2002; Reinhardt et al. 2002; McManus et al. 2003; Miller et al. 2007; Herrmann et al. 2007; Cuevas 2010; Ekman and Börjesson 2011). In addition, the available studies are often incomplete or lack transparency.

ValBiom (the authors' organization) is a Belgian association which promotes the use of biomass for non-food applications while respecting the principles of sustainable development. Within the framework of its mission, the association has been supporting the development of biolubricants for many years. For this purpose, it notably conducted numerous experiments to demonstrate their technical performance on the field (ValBiom 2003; Novak 2004a). It also performed studies on the environmental and health risks associated with these oils (Novak 2004b; ValBiom 2005) to improve the knowledge among users on their specific properties. In parallel, ValBiom has also been encouraging development projects on the farm. One of the projects being supported is a project for producing chainsaw oil on the farm.

In order to better understand the environmental impacts of biolubricants, this biobased chainsaw oil made on the farm was chosen as an example by ValBiom. The environmental issue is indeed a particular concern for chainsaw oils because these lubricants represent a total loss system with the oil being flung off the chain and lost into the environment. Consumption estimates by ValBiom indicate that 350,000 l of chainsaw oil is released each year in the Walloon (southern Belgium) forest alone, the majority being mineral oil based. Three papers were found focusing on life cycle assessment applied to the chainsaw oil application (Wightman et al. 1999a, b; Reinhardt et al. 2002), but these papers were poorly documented.

The objective of this study is twofold. The first objective is to quantify the environmental impacts of this specific chainsaw oil made on the farm in Wallonia and to compare it with a model mineral chainsaw oil, integrating the previous life cycle assessments (LCAs) on lubricants and biolubricants. Steps and parameters that contribute most to the environmental load of these two systems are identified. A sensitivity analysis is also performed to illustrate the influence of different modelling assumptions on the results.

The second objective is to participate in the development of the LCA methodology applied to the biolubricant sector. This detailed study could be useful for conducting LCA on other biodegradable commercial chainsaw oils since the chemistry of this type of oils is based, for economical reasons, on the use of vegetable oils and not on synthetic esters (from petrochemical or oleochemical origin).

2 Methodology

The general framework for conducting this LCA is found in ISO 14040 and ISO 14044 standards (ISO 2006a, b). The biobased chainsaw oil made on the farm in Wallonia and a model mineral oil-based chainsaw oil are studied. The LCA is from cradle to grave.

2.1 Functional unit

The function of chainsaw oils is to lubricate the chain of chain saws. The common functional unit we chose is 1 kg of base oil. In this study, it is assumed that both oils have the same technical characteristics.

[1] In this study, the term "biobased products" is based on the definition given by the European Commission in the framework of the Lead Market Initiative and refers to products made entirely or partly from renewable biological raw materials such as plants and trees. This definition excludes food, traditional paper and wood products and biomass as an energy source.

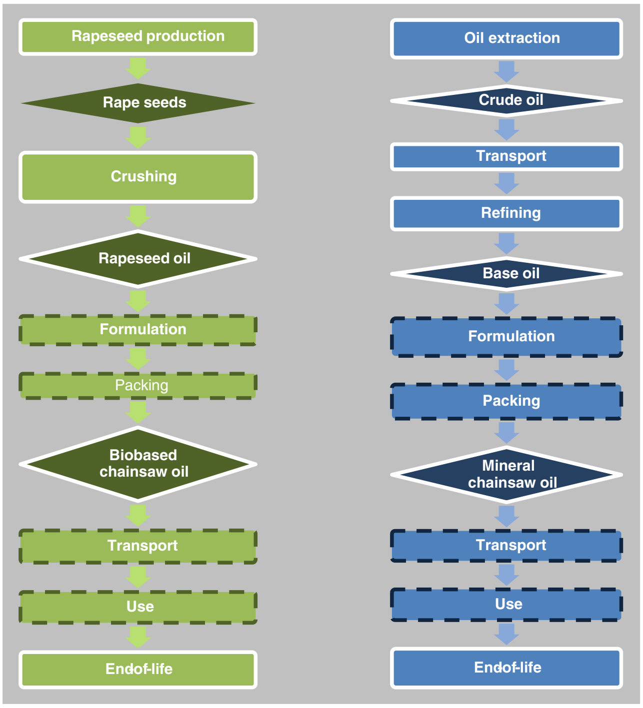

Fig. 1 Schematics of the chainsaw oil systems considered in this study. *Dotted lines* indicate the stages that are excluded from the life cycle assessment

2.2 System delimitation

In Fig. 1, the simplified boundaries for the biobased chainsaw oil and the fossil reference system are shown. The biobased chainsaw oil system includes the agricultural stage which results in rape seeds, the crushing stage at the farm transforming the seeds in rapeseed oil and the end of life of the oil (when the oil is used, its ends up directly and in its entirety in the surrounding environment). The fossil chainsaw oil system includes the step of crude oil extraction, its transport to a refinery, the refining of crude oil into lubricant base oil and the end of life of the oil (it also ends up directly and in its entirety in the environment).

Certain processes or inputs were excluded from the studied systems when data were not available or when processes were similar for the compared systems (their omission not influencing the results significantly). For both systems, the use phase was not considered because it was assumed to be identical (no measurement was made on the field to measure the oil consumption, so it was assumed that the same quantity of oil was consumed in both systems to perform the same work). In both systems, the formulation phase was not considered because of the lack of data concerning the additives. In the sensitivity analysis, the impact of taking lubricating additives typically used in biobased and mineral chainsaw oils into account is studied. Similarly, the packing stage was not taken into consideration to ensure uniformity between both systems because data were not available for the fossil system. Finally, the transportation of the oil from the farm (for the biobased oil) or from the refinery (for the fossil reference) to a distributor or a final consumer was not considered because of the difficulty of modelling such a transport (no traceability for the biobased chainsaw oil and no data for the fossil reference).

The infrastructure, i.e., the amount of equipment and the amount of site required to perform the functional unit, was not taken into consideration in both systems due to the difficulty of modelling them (Which amount of infrastructure can be attributed to the oil? Which allocation between products and co-products? Which projected life time of the equipment?…).

2.3 Data collection

Life cycle inventories of inputs and outputs were implemented for each chainsaw oil. In order to provide as comprehensive a picture of the systems as possible, identifiable upstream processes for the systems and the subsystems studied were included.

2.3.1 Biobased chainsaw oil

Crop production The data collected for rapeseed cultivation in Wallonia were mainly derived from an agricultural survey conducted in 2009 by APPO, a Walloon association that promotes oil seeds and protein plants. These data were considered representative of current agricultural practice in Wallonia.

Concerning mechanization, the number of crossings on the yield and the typical equipments used were determined with APPO based on the survey. Then, diesel consumption was calculated using MECACOST tool (Rabier and Miserque 2009) that was developed by the Walloon Agricultural Research Center. In this tool, diesel consumption is obtained by multiplying the power of the engine by the motor use rate and by the specific fuel consumption. The motor use rate needs to be adapted according to the mounted implement which is used. Coherence of the agricultural equipments used as well as the adjustments of the motor use rate for each combination tractor-mounted implement was checked by the Walloon Agricultural Research Center. Diesel consumption associated with the transport from field to farm for each agricultural operation was also taken into account.

Regarding fertilization, the quantity of nitrogen spread on the field was taken from the survey. Survey forms that included both mineral and organic fertilization were discarded because data on organic fertilization were not precise enough to be taken into account. Nitrogen in the crop residues from the

previous crop and nitrogen returned by the rapeseed crop were taken from a French study on biofuels (Ademe 2010) since such data were not available in Wallonia. Inputs of phosphorus and potassium were determined from the estimation of phosphorus and potassium exported by the crop (P_20_5 and K_20 being applied for the whole crop rotation) using CORPEN reference for rape seeds (Ministère de l'agriculture de la, de la pêche, de la ruralité et de l'aménagement du territoire 2011). Input of sulphur was determined from the survey.

Pesticides were determined based on the APPO survey. The most frequently used pesticides were selected, and the consumption of active substances was determined on the basis of the recommended dosages.

Input of seeds was determined based on the APPO survey, and the rape seeds production phase was considered by using ecoinvent 2.2 life cycle inventory called "Rape seed IP, at regional storehouse/CH" (Nemecek et al. 2007).

The data used in the inventory are compiled in Table 1.

The study of the agricultural phase also includes background information and hypotheses that are summarized in Table 2.

In Wallonia, rapeseed is grown in non-irrigated soils mainly under conventional tillage. It is considered entering into the following typical crop rotation scheme: row barley–rapeseed–wheat. Based on the APPO survey, the rapeseed production in Wallonia for year 2009 was 4.924 t/ha. This data was kept because all the other agricultural data from the survey referred to the year 2009, but in the sensitivity analysis, the influence of an average rape seeds yield in the period 1999–2009 was studied.

Storage and crushing of the seeds The data collected for the storage of the seeds and the extraction of rapeseed oil are based on the installation of the Walloon farmer that produces and markets the biobased chainsaw oil.

During storage of the seeds, ventilation is carried out (in order to increase their storage life) with a vertical fan system operated with two 1.10-kW motors during 7 days (49 h). Seeds are then loaded in the press with a telescopic loader.

As regards the extraction, a 7.5-kW expeller pressing is used having a delivery rate of 100 kg of seeds per hour. The removal of impurities is done by decantation and filtration. The yield ratios for the extraction step are illustrated in Table 3. The consumptions associated with the storage and crushing stages are compiled in Table 4.

2.3.2 Mineral chainsaw oil

Extraction of crude Today, most refineries in the world produce base oils from paraffinic crude (Mortier et al. 2010). Therefore, the extraction of crude oil was assumed to take place in the Middle East as the Middle East is a typical source of paraffinic crude oil and is one of the most important import areas for imported crude in Europe (Energy-Redefined LLC 2010). LCI data for the extraction of crude oil and its transport to a European refinery were taken from Eurobitume (2011) (see Electronic Supplementary Material).

Base oil manufacture Base oil manufacture was located in the Amsterdam-Rotterdam-Anvers area. In this study, mass and energy flows along the base oil production chain were calculated based on the yields and on the fuel selection for energy supply from Fehrenbach (2005) that refers to a virtual European base oil refinery. In this virtual refinery, the base oil manufacturing process consists of a series of seven steps to separate the desirable lube base oil from the bulk of the crude oil: atmospheric distillation, vacuum distillation, deasphalting, solvent extraction, high-pressure hydrogenation, dewaxing and hydrofinishing. The different yield ratios of products and the mass and energy flows by the base oil production chain are given in the Electronic Supplementary Material. Our study assumes that 17.1 % of the crude oil used for making base oil effectively results in base oil. This ratio is a little higher than yields usually described in literature that range between 1 and 12 % (European Commission 2003; Miller et al. 2007; Clarens et al. 2008; Girotti et al. 2011; Raimondi et al. 2012). Raimondi et al. (2012) and Girotti et al. (2011) used the same reference (Fehrenbach 2005), but their ratio was 11.2 %. This was due to a difference in the process flowchart at the vacuum residue and at the deasphalting stages. In the sensitivity analysis, the impact of higher extraction yields in the production of the base oil, leading to a lower base oil yield, is studied. For all refining stages, only process water was taken into account as cooling water was assumed to be entirely recycled in the refinery. For the solvent extraction step, we assumed that only 2 NMP (*N*-methyl-2-pyrrolidone) was used since furfural was not available in the ecoinvent database. For the dewaxing step, we assumed that dichloromethane was used instead of Di-Me (because dichloroethane–dichloromethane mixture was not available in the ecoinvent database).

2.4 Calculation of emissions

2.4.1 Biobased chainsaw oil

Crop production Calculation of air emissions generated from the combustion of diesel is based on Nemecek et al. (2007). Emissions (and consumptions) associated with the production and storage of diesel were estimated using the ecoinvent 2.2 life cycle inventory called "Diesel, at regional storage/RER".

Table 1 Inventory of agricultural inputs (per 1 ha) for rapeseed cultivated in Wallonia

Input	Unit	Value	Detail	Source
Diesel consumption				
Stubble ploughing	L	8.4	Tractor—4-wheel drive, 140 hp and a mounted tine stubble (Number of crossings: 1)	APPO survey for winter rape in Wallonia in 2009 and APPO
Soil preparation	L	19.04	Tractor—4-wheel drive, 110 hp and a mounted plough with 4 ploughshares (Number of crossings: 1)	
Sowing	L	13.2	Tractor—4-wheel drive, 140 hp and a combined seed drill/harrow (Number of crossings: 1)	
Fertilizing	L	3.34	For P and K fertilization and solid N et S fertilization: Tractor—2-wheel drive, 80 hp and a mounted centrifugal fertilizer distributor 18–24 m (2,000 l) (Number of crossings: 2) For liquid N fertilization: Tractor—4-wheel drive, 110 hp and a trailed sprayer DPA 3,000 l (24–28 m) (Number of crossings: 1)	
Pesticide application	L	8.5	Tractor—4-wheel drive, 110 hp and a trailed sprayer DPA 3,000 l (24–28 m) (Number of crossings: 6)	
Harvesting	L	19.34	Combine harvester, 250 hp, with 5 agitators 5 m (Number of crossings: 1)	
Transport of the harvest from field to farm	L	1.25	Tractor—4-wheel drive, 110 hp and a 14-m^3 dump with 2 axles (Number of crossings: 1)	
Transport between field and farm for all the agricultural operations	L	3.57	Refer to the material used in each agricultural operation	
Pesticides				
Thiacloprid	kg	0.072		APPO survey for winter rape in Wallonia in 2009 and APPO
Lambda-cyhalothrin	kg	0.006		
Metazachlore	kg	1		
Quinmerac	kg	0.25		
Clomazone	kg	0.12		
Boscalid	kg	0.25		
Metconazole	kg	0.072		
Fertilization				
Urea ammonium nitrate (as N)	kg	128.4		APPO survey for winter rape in Wallonia in 2009 and APPO
Ammonium sulphate (as N)	kg	49		
Monoammonium phosphate (as P_2O_5)	kg	68.9		
Potassium sulphate (as K_2O)	kg	50		
Seed				
Rape seeds	kg	2.6		APPO survey for winter rape in Wallonia in 2009

The air and water emissions from application of fertilizers were estimated based on Nemecek et al. (2007), IPCC guidelines (IPCC 2006) and Prasuhn (2006). The estimation of ammonia (NH_3) emissions from the application of urea

Table 2 Main hypotheses for the agricultural phase

	Hypothesis	Source
Rape seeds	4.924 t/ha	Survey for winter rape in Wallonia in 2009 (APPO)
Seeds average humidity	9 % *w/w*	APPO
Crop rotation scheme	Row barley–rapeseed–wheat	APPO
N content in previous crop residues	50 kg N/ha	ADEME (2010) (data agreed by APPO)
N content in rapeseed residues	60 kg N/ha	ADEME (2010) (data agreed by APPO)

ammonium nitrate, ammonium sulphate and monoammonium phosphate was estimated according to the method described in Nemecek et al. (2007). The N_2O emissions were estimated based on the emission factors from IPPC guidelines. Estimation of NO_x emissions was based on Nemecek et al. (2007). Nitrate (NO_3^-) leaching was estimated according to the method described in the IPCC guidelines. Emissions of phosphate (PO_4^{3-}) through leaching and run-off and of phosphorus through erosion of soil particles were calculated based on Prahsun (2006). Emissions associated with the production of the fertilizers were estimated using the corresponding ecoinvent 2.2 life cycle inventories.

Calculation of emissions in the air associated with pesticide application was based on the EMEP-CORINAIR method (EMEP/EEA 2009) which is based on the vapour pressure of the active substances. The emissions of active substances in the soil and in water were calculated with the method of Audsley et al. (1997). Emissions associated with the production of pesticides were estimated using the corresponding ecoinvent 2.2 life cycle inventories. When specific data were not available for the production of specific pesticides, generic ecoinvent data were taken.

Emissions associated with the production of rape seeds were estimated using the ecoinvent 2.2 life cycle inventory called "Rape seed IP, at regional storehouse/CH".

Emissions of heavy metals to soil, surface and groundwater from seeds, fertilizers, pesticides and atmospheric deposition were calculated based on Nemecek et al. (2007).

Table 3 Yield ratios for the extraction of rapeseed oil and the removal of impurities

	Mass yield per process step (%)
Extraction	
Raw rapeseed oil	34
Press cake	66
Removal of impurities	
Decantation	
Decanted oil	95.5
Impurities	4.5
Filtration	
Filtered oil	95.5
Impurities	4.5
	Total products yield by the transformation chain (%)
Filtered rapeseed oil	31
Press cake	66
Impurities	3

Storage and crushing of the seeds The emissions due to the production of electricity were given in the life cycle inventory of the ecoinvent 2.2 database called "Electricity, low voltage, production BE, at grid/BE". The emissions due to the production of diesel were given in the life cycle inventory of the ecoinvent 2.2 database called "Diesel, at regional storage/RER". The emissions resulting from the combustion of diesel were calculated based on Nemecek et al. (2007).

End of life In this study, we assumed that the biobased chainsaw oil is entirely and rapidly biodegraded once dispersed in the environment. The oil is indeed evaluated as readily biodegradable according to the OECD 301B biodegradability test (OECD 1992), i.e., the oil biodegrades more than 82 % over a 28-day period when exposed to certain microorganisms. This means that the carbon in the oil is rapidly released in the form of CO_2.

In our study, we decided not to take into account the CO_2 emissions arising at the end-of-life stage of the biobased chainsaw oil assuming that the same quantity of CO_2 is absorbed by rapeseed during photosynthesis. To justify this, it is also important to note that:

- Carbon storage in the chainsaw oil is not taken into account: eventual storage in the chainsaw oil (corresponding to the interval between the time of manufacture of the oil and its use on the field) was not taken into account assuming carbon sequestration and delay of CO_2 emission was analogous for the biobased and the fossil chainsaw oils.

Table 4 Consumption of the process steps of rapeseed oil production (storage and crushing)

	Value	Unit (all data per ton of input)
Ventilation of seeds		
Electricity	25.9	MJ
Extraction		
Diesel	0.43	MJ
Electricity	270	MJ
Removal of impurities		
Electricity (decantation)	0.4	MJ
Electricity (filtration)	11.6	MJ

- There is no carbon storage in the plant: rapeseed is an annual crop with a land use period of 10 months in Wallonia.
- Direct emissions of carbon related to soil transformation processes are considered null. The agricultural lands for growing rapeseed in Wallonia have been used for an agricultural purpose for many years (for more than 20 years). Indirect emissions related to land use change were not considered due to the absence of scientific consensus on best how accounting for them.
- Biodegradation of the oil is supposed to occur under aerobic conditions. As a result, biodegradation results in CO_2 and not in CH_4 (that we should have taken into account if it has been emitted given its higher global warming potential).

2.4.2 Mineral chainsaw oil

Extraction of crude Emissions associated with the extraction and the transport of crude are derived from Eurobitume (2011) (see the Electronic Supplementary Material).

Base oil manufacture Emissions associated with consumption and combustion of heavy fuel oil, refinery gas and natural gas were estimated using the corresponding ecoinvent 2.2 life cycle inventories. Emissions associated with petroleum coke consumption were also based on figures provided by the ecoinvent 2.2 database, but emissions related to its combustion were calculated according to the method described in the IPCC guidelines (IPCC 2006). As refinery effluents were variable in their composition, they were not modelled in this study. Emissions associated with the consumption of 2 NMP (*N*-methyl-2-pyrrolidone), dichloromethane and with methyl ethyl ketone were taken from the ecoinvent 2.2 database.

End of life Most mineral base oils are not readily biodegradable in standard 28-day ready biodegradability tests (OECD 1992). But since they consist primarily of hydrocarbons which are ultimately assimilated by microorganisms, they are considered to be inherently biodegradable which means they biodegrade at least 20 % within the 28 days (Concawe 1997). The slow biodegradation of mineral base oils is due to oil components that are difficult to biodegrade (Vahaoja et al. 2005).

To the best of our knowledge, no study presents the biodegradation kinetics of mineral base oils over a sufficiently long period of time that would allow taking into account a time-delayed release of CO_2. For this reason, we assumed that CO_2 emissions occur at the time the oil is released into the environment. As for the biobased chainsaw oil, we did not take into account an eventual storage in the chainsaw oil corresponding to the interval between the time of manufacture of the oil and its use on the field. We also assumed that the biodegradation of the mineral chainsaw oil occurs under aerobic conditions only (abiotic degradation is considered minor in degradation of mineral oil according to Vahaoja et al. 2005). The carbon content of the mineral base oil was estimated to be around 84 % *w/w* (Vahaoja et al. 2005) which is equivalent to an emission of 3.08 kg of CO_2 emitted per kilogram of base oil.

2.5 Impact categories and methods for impact assessment

We selected the following seven impact categories: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), photochemical oxidation potential (POP), aquatic eutrophication potential with marine eutrophication (MEP) and freshwater eutrophication (FEP), aquatic ecotoxicity potential (EP) and abiotic depletion potential (ADP).

Characterization factors used for assessment are derived from the following methods: ReCiPe (ReCiPe Midpoint (H) v1.05/Europe ReCiPe H, Goedkoop et al. 2008), Usetox (Rosenbaum et al. 2008), CML (CML 2 baseline 2000 v2.05, Guinée et al. 2002) and IPPC (IPCC 2007 GWP 100a v1.02, IPCC 2007). The choice of the method to apply for modelling each impact category was made on the basis of the recommendations issued by the International Reference Life Cycle Data System (European Commission 2011). For acidification potential, we did not use the recommended method based on accumulated exceedance (Seppälä et al. 2005; Posch et al. 2008) because it is not yet readily available in impact assessment methodologies. For this impact category, CML was chosen as it was globally reaching a good evaluation.

2.6 Calculation of aquatic ecotoxicity potential

USEtox is a scientific consensus model (Hauschild et al. 2008) for impact characterization related to human toxicity and

freshwater ecotoxicity. In our study, we used this model for the aquatic toxicity only. In USEtox, the characterization factors for freshwater ecotoxicity are expressed in comparative toxic units (CTUe) and provide an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF.m^3.day/kg).

This model also provides a database with already calculated characterization factors for more than 3,000 substances. Three of the seven active substances inventoried in the agricultural stage of the biobased chainsaw oil were not recorded in this database: thiacloprid, boscalid and metconazole. As pesticides are one of the major environmental issues linked with agriculture (Berthoud et al. 2011), we decided to calculate the characterization factors for these three substances thanks to the USEtox calculator.

2.7 Allocation procedure

2.7.1 Biobased chainsaw oil

As regards the crop production, the entire environmental cost was attributed to the seeds because rapeseed straws are generally not harvested in Wallonia. As regards the crushing phase, we used a mass-based allocation to assign the environmental burdens between rapeseed oil and rapeseed meal. This procedure was not the most appropriate procedure because it underestimates the importance of the oil compared to rapeseed meal, but it was chosen to ensure the uniform application of allocation procedure between the biobased and the fossil chainsaw oil. In the sensitivity analysis, the impact of using energy allocation in the production of the rapeseed oil is studied. For the removal of impurities, the entire environmental cost was attributed to the oil.

2.7.2 Mineral chainsaw oil

The allocation at the crude oil extraction and the transport stages was based on mass balance. At these stages, it was considered that all the products extracted from crude oil (gasoline, base oil, heavy fuel oil…) were still blended and can be considered as raw materials for which a mass relationship can be established (Eurobitume 2011).

As regards the refining stage, a mass-based allocation was chosen. The energetic allocation was not chosen since the energy values of the different refining products only slightly deviate from the one of crude oil (IEA 2009). Economic allocation was not chosen because of its greater uncertainty. This uncertainty was for intermediate flows which are raw materials for subsequent refining steps or which serve as fuels for the refinery and therefore which are not intended to be sold on the market. In addition, the prices of the different refined products fluctuate over time subject to market demand which is likely to make results deriving from an economic allocation procedure fluctuate.

3 Impact assessment results

3.1 Characterized results

Table 5 shows the potential environmental impacts for the life cycle of the biobased and the mineral chainsaw oils. A comparison of the results shows that the biobased chainsaw oil has a lower impact in four out of the seven impact categories, i.e. for the GWP, the ADP, the ODP and the POP. The biobased chainsaw oil has a higher impact for the aquatic eutrophication potential (MEP and FEP), the EP and the AP.

In order to further validate the results of this study, we compared them to results from other studies. As LCA results are largely dependent on lubricant application, we decided to limit the comparison to the production of the base oil. Tables 6 and 7 provide therefore a comparison of the potential environmental impacts of rapeseed oil and of mineral base oil production across different relevant comparative studies (Ekman and Börjesson 2011; Cuevas 2010; McManus et al. 2003). Three studies that only studied rapeseed oil (Schmidt 2010) or mineral oil (Raimondi et al. 2012; Girotti et al. 2011) production were also added for comparison purpose. Although the presented values differ from ours for the same type of oil, our conclusions regarding the comparison between both types were identical with those of Ekman and Börjesson (2011). As regards Cuevas (2010) results, conclusions were identical except for POP. As regards McManus et al. (2003) results, conclusions were identical only for GWP and FEP. Concerning the mineral base oil, our results were very similar to those of Girotti et al. (2011) and Raimondi et al. (2012) except for POP. Concerning the rapeseed oil, the contributions of rapeseed oil production in Schmidt (2010) were higher than those from our study.

3.2 Process contribution

Figure 2 gives the relative contribution of the different stages of the life cycle of the two chainsaw oils on the overall environmental impact. The detailed information for each impact category is given in the following subsections.

3.2.1 Global warming potential

The contribution to GWP is approximately 5.9 times higher for the mineral chainsaw oil than for the biobased one.

Table 5 Environmental impacts expressed per 1 kg of the biobased and the mineral chainsaw oils

Impact category/indicator	Biobased chainsaw oil	Mineral chainsaw oil
Global warming potential (kg CO_2 eq.)	0.66	3.89
Ozone depletion potential (kg CFC-11 eq.)	4.35E−08	1.34E−07
Abiotic depletion potential (kg Sb eq.)	1.98E−03	5.27E−03
Acidification potential (kg SO_2 eq.)	9.70E−03	8.64E−03
Photochemical oxidation potential (kg NMVOC eq.)	1.34E−03	3.36E−03
Freshwater eutrophication potential (kg P eq.)	7.45E−04	2.07E−05
Marine eutrophication potential (kg N eq.)	5.49E−03	9.13E−04
Aquatic ecotoxicity potential (CTU eq.)	5.82	2.99E−01

For the mineral chainsaw oil, the end of life contributes about 79 % of the total GWP due to the fossil CO_2 released into the environment.

For the biobased chainsaw oil, the agricultural stage contributes by far the most to GWP with 95 % of the total load. This result is in agreement with previous studies that indicate the high contribution of the agricultural phase to GWP for biobased lubricants (Wightman et al. 1999b; Ekman and Börjesson 2011). In the agricultural phase, the fertilizers are the agricultural inputs with the highest environmental impact: 52 % of the impact associated with the agricultural phase is due to field N_2O emission associated with fertilizer application, and 38 % of the impact is due to fertilizers themselves (production and transportation to the regional storehouse in Europe). These results are also in agreement with those of Kaltschmitt et al. (1997), Schmidt (2010), Iriarte et al. (2010) and Ekman and Börjesson (2011) that indicate the high contribution of fertilizers (and their field emissions) to GWP in rapeseed cultivation.

3.2.2 Ozone depletion potential

The contribution to ODP is approximately 2.5 times higher for the mineral chainsaw oil than for the biobased one.

For the mineral chainsaw oil, the refining stage contributes about 89 % of the total ODP. In this stage, 71 % of the impact is due to Halon 1301 emissions. Halon chemicals were widely used as fire-suppressing systems in oil

Table 6 Environmental impacts of the production of rapeseed oil in different studies

	McManus et al. (2003)		Cuevas (2010)		Schmidt (2010)		Ekman and Börjesson (2011)		This study	
	Val.	Unit	Val.	Unit	Val.	Unit	Val.	Unit	Val.	Unit
Functional unit	1	kg	1	kg	1	kg	1	L	1	kg
Global warming potential	0.3	kg CO_2 eq.	−3.62E−01	kg CO_2 eq.	2.22	kg CO_2 eq.	0.75	kg CO_2 eq.	0.66	kg CO_2 eq.
Ozone depletion potential	4.25E−10	kg CFC-11 eq	2.83E−07	kg CFC-11 eq	1.63E−07	kg CFC-11 eq	–	–	4.35E−08	kg CFC-11 eq
Abiotic depletion potential	–	–	–	–	–	–	–	–	1.98E−03	kg Sb eq.
Acidification potential	3.27E−03	kg SO_4^{2-} eq.	2.70E00	H^+ moles eq.	2.02E−02	kg SO_2 eq.	7.4E−03	kg SO_2 eq.	9.70E−03	kg SO_2 eq.
Photochemical oxidation potential	4.79E−04	kg C_2H_4 eq	2.29E−02	kg NO_x eq.	0.89	kg C_2H_4 eq	0.02	kg C_2H_2 eq	1.34E−03	kg NMVOC eq.
Freshwater eutrophication potential	1.02E−03	kg PO_4^{3-} eq.	–	–	–	–	1.02E−03	kg PO_4^{3-} eq.	7.45E−04	kg P eq.
Marine eutrophication potential	–	–	7.61E−02	kg N eq.	1.40E−01	kg NO_3 eq.	–	–	5.49E−03	kg N eq.
Aquatic ecotoxicity potential	–	–	1.78	kg 2.4 D eq.	–	–	–	–	5.82	CTU eq.

Table 7 Environmental impacts of the production of mineral-based oil in different studies

	McManus et al. (2003)		Cuevas (2010)		Girotti et al. (2011)		Ekman and Börjesson (2011)		Raimondi et al. (2012)		This study	
	Val	Unit	Val	Unit	Val	Unit	Val	Unit	Val	Unit	Val	Unit
Functional unit	1	kg	1	kg	1	kg	1	L	1	kg	1	kg
Global warming potential	3.56	kg CO_2 eq.	1.07	kg CO_2 eq.	1.02	kg CO_2 eq.	1.75	kg CO_2 eq.	0.99	kg CO_2 eq.	0,81	kg CO_2 eq.
Ozone depletion potential	8.90E −12	kg CFC-11 eq	6.48E −07	kg CFC-11 eq	7E −07	kg CFC-11 eq	–	–	7.0E −07	kg CFC-11 eq	1.34E −07	kg CFC-11 eq
Abiotic depletion potential	–	–	–	–	–	–	–	–	–	–	5.27E −03	kg Sb eq.
Acidification potential	3.83E −03	kg SO_4^{2-} eq.	4.58E −01	H^+ moles eq.	8.4E −03	kg SO_2 eq.	4.05E −03	kg SO2 eq.	2.2E −02	kg SO_2 eq.	8.64E −03	kg SO_2 eq.
Photochemical oxidation potential	1.61E −08	kg C_2H_4 eq	3.09E −03	kg NO_x eq.	0.89	kg NMVOC eq.	0.81	kg C_2H_4 eq	–	–	3.36E −03	kg NMVOC eq.
Freshwater eutrophication potential	3.78E −04	kg PO_4^{3-} eq.	–	–	9.3E −06	kg P eq.	8.20E −05	kg P eq.	3.26E −04	kg P eq.	2.07E −05	kg P eq.
Marine eutrophication potential	–	–	2.31E −02	kg N eq.	1E −03	kg N eq.	–	–			9.13E −04	kg N eq.
Aquatic ecotoxicity potential	–	–	1.21	kg 2,4 D eq.	–	–	–	–			2.99E −01	CTU eq.

refineries. This production and use have been heavily restricted since the Montreal Protocol in 1987. European refineries have probably experienced a heavy reduction in the consumption and emission of Halon 1301 since then, but more recent data have not been available.

For the biobased chainsaw oil, the agricultural stage contributes by far the most to ODP with 94 % of the total load. In this stage, 46 % of the impact is due to fertilizers (production and transportation to the regional storehouse in Europe) and 35 % to pesticides (production and transportation to the regional storehouse in Europe).

3.2.3 Abiotic depletion potential

The global contribution to ADP is approximately 2.7 times higher for the mineral chainsaw oil than for the biobased one.

For the mineral chainsaw oil, the refining stage plays a significant role with a contribution of 86 % to the total load. This can be explained by the fact that lubricant base oil production is a very energy-intensive process.

For the biobased chainsaw oil, the most significant stage contributing to ADP is the agricultural stage with 87 % of the total load. In this stage, 75 % of the impact is due to fertilizers (production and transportation to the regional storehouse in Europe).

3.2.4 Photochemical oxidation potential

The global contribution to POP is approximately 2.3 times higher for the mineral chainsaw oil than for the biobased one.

For the mineral chainsaw oil, the extraction stage contributes 52 %, and the refining stage contributes 48 % of the total load. NO_x, SO_2 and non-methane volatile organic compounds (NMVOC) emissions due to combustion processes are mainly responsible for this impact.

For the biobased chainsaw oil, the agricultural stage contributes by far the most to POP with 94 % of the total load. In this stage, 47 % of the impact is due to fertilizers (production and transportation to the regional storehouse in Europe) and 47 % of the impact is due to emissions of NO_x associated with nitrogen fertilization and with combustion of diesel.

3.2.5 Acidification potential

The global contribution to AP is approximately 1.1 times higher for the biobased chainsaw oil than for the mineral one.

For the biobased chainsaw oil, this impact is mainly due to the agricultural stage which contributes about 99 % of the total load. In this stage, 79 % of the impact is due to ammonia (NH_3) emissions related to nitrogen fertilization.

For the mineral chainsaw oil, the refining stage contributes 68 % and the extraction stage contributes 32 % of the

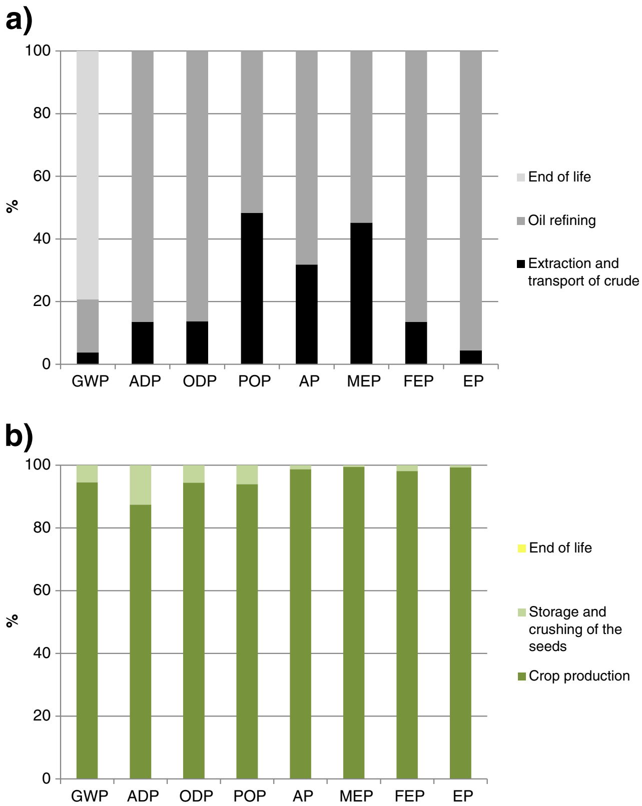

Fig. 2 Contribution of the life cycle stages to the overall environmental impact of the mineral (**a**) and the biobased (**b**) chainsaw oils. The total impact is shown as 100 %

total load. In both stages, impact is due to SO_2, NO_x and NH_3 emissions arising from combustion processes.

3.2.6 Aquatic eutrophication

Marine eutrophication potential The global contribution to MEP is approximately six times higher for the biobased chainsaw oil than for the mineral one.

For the biobased chainsaw oil, this impact is mainly due to the agricultural stage which contributes about 99 % of the total load. This impact mainly results from the leaching of the nitrogen nutrients (96 %).

For the mineral chainsaw oil, the refining stage and the extraction stage contribute almost equally to the total load (55 and 45 %, respectively). For both stages, this impact is mainly due to NO_x emissions arising from combustion processes.

Freshwater eutrophication potential The global contribution to FEP is approximately 36 times higher for the biobased chainsaw oil than for the mineral one.

For the biobased chainsaw oil, the most significant stage contributing to FEP is the agricultural stage with 98 % of the total load. This impact mainly results from the leaching of the phosphorus nutrients (57 %). Unlike nitrogen emissions, phosphorus emissions also depend on erosion and therefore are also related to the soil characteristics in Wallonia.

For the mineral chainsaw oil, the refining stage contributes the most with 87 % of the total load. This impact is mainly due to NO_x emissions arising from combustion processes.

3.2.7 Aquatic ecotoxicity potential

The global contribution to the aquatic EP is approximately 20 times higher for the biobased chainsaw oil than for the mineral one.

For the biobased chainsaw oil, this impact is mainly due to the agricultural stage which contributes more than 99 % of the total load. In this stage, around 72 % of the impact is due to the emission of active substances related to pesticide application.

For the mineral chainsaw oil, the impact is mainly due to the refining stage which contributes about 96 % of the total load. In this stage, the impact is mainly due to heavy metal emissions arising from the combustion of fossil fuels.

It is important to note that some common toxic substances such as methane, carbon monoxide, aluminium and ammonia, and groups of substances such as PAH, hydrocarbons, NMVOC and particulates are missing in the USEtox database. For example, emissions of petroleum into the air and into water in the mineral chainsaw oil life cycle were not taken into account by USEtox, and because of this, the aquatic ecotoxicity potential of the mineral chainsaw oil is maybe underestimated.

4 Sensitivity analysis

As LCA results are closely linked to modelling assumptions, it is very important to assess to what extent a variation in the choice of the assumptions can influence the results and to check if this variation can reverse the results. For this purpose, we performed a sensitivity analysis.

To perform this analysis, the value of the assumptions that were considered uncertain was modified with other plausible value. The LCA results were then re-evaluated, and their robustness was tested for sensitive parameters.

We assumed that an assumption was “sensitive” if the variation applied brought a change of at least 10 % in the final result in one of the impact category studied. If the change was lower than 10 %, then the assumption was considered “non sensitive”. In total, seven sensitivity analyses were performed.

4.1 Rape seeds yield

In the reference case, the rape seeds yield was 4924 kg/ha based on an agricultural survey conducted in 2009. In order

to evaluate the influence of a change in the rape seeds yield, an average of the yields over the period 1999–2009 was used which amounted to 4,068 kg/ha (APPO 2009).

Results are shown in Table 8 where the final results obtained using the above-mentioned yield are compared with the fossil reference system. They show that, even if the parameter is evaluated as “sensitive” (results are increased by about 20 % for all impact categories), conclusions are not reversed.

4.2 Active substance replacement and effects on the results

Lambda-cyhalothrin emissions were identified as preponderant in the aquatic ecotoxicity score of the biobased chainsaw oil representing 68 % of overall score. Based on the list of pesticides authorized for use on rapeseed in Wallonia, we evaluated the influence of the use of three other active substances (cyfluthrin, cypermethrin and deltamethrin) having the same agronomic role. Then, the environmental impact of the biobased chainsaw oil in terms of aquatic ecotoxicity was re-evaluated.

Results are shown in Table 8. The substitution of lambda-cyhalothrin by deltamethrin contributed to a decrease of the aquatic ecotoxicity potential of 66 %. On the contrary, the substitution by cypermethrin or cyfluthrin contributed to an increase of 36 and 536 % respectively.

4.3 Chainsaw oil consumption

In this study, we assumed that the chainsaw oil consumption was identical whatever the type of oil used. In this sensitivity analysis, the environmental impact of the biobased chainsaw oil was re-evaluated considering it is necessary to use 1.5 times more biobased chainsaw oil than mineral one.

Results are shown in Table 8. They show that, even if the parameter is evaluated as “sensitive” (results are increased by more than 10 % for all impact categories), conclusions are not reversed. A quick simulation shows that it would be necessary to use 2.1 times more biobased than mineral chainsaw oil to reverse the conclusion concerning the ozone depletion potential and to use 5.8 times more biobased chainsaw oil to reverse conclusions concerning the ozone depletion potential, the abiotic depletion potential, the photochemical oxidation potential and the global warming potential.

However, according to tests performed in the field by professional loggers to evaluate the technical performance of the biobased chainsaw oil, such consumption differences were considered unlikely.

4.4 Additivation

Most LCAs related to lubricants do not consider the influence of additives (Våg et al. 2002; McManus et al. 2003; Miller et al. 2007; Clarens et al. 2008; Cuevas 2010; Ekman and Börjesson 2011). There is either no justification for explaining this (McManus et al. 2003; Clarens et al. 2008) or the justification is that they constitute a small percentage of the total lubricant (Cuevas 2010) or their contribution is assumed to be negligible (Ekman and Börjesson 2011). For comparative LCAs, some authors also argue that the additives in the compared systems are similar (Miller et al. 2007). This situation can be explained by the lack of detailed and reliable LCI for additives, by the huge variety of

Table 8 Results of the sensitivity analyses expressed in percentage change in comparison of the baseline scenarios

Assumptions		Baseline scenario	GWP (kg CO_2 eq.)	ODP (kg CFC-11 eq.)	ADP (kg Sb eq.)	AP (kg SO_2 eq.)	POP (kg NMVOC eq.)	FEP (kg P eq.)	MEP (kg N eq.)	EP (CTU eq.)
Rape seeds yield	Average rapeseeds yield (1999–2009)	BCO	+20	+20	+19	+21	+20	+21	+21	+21
Active substances	Deltamethrin	BCO	0	0	0	0	0	0	0	−66
	Cypermethrin	BCO	0	0	0	0	0	0	0	+36
	Cyfluthrin	BCO	0	0	0	0	0	0	0	+536
Chainsaw oil consumption	1.5 times more biobased chainsaw oil	BCO	+50	+50	+50	+51	+50	+50	+50	+50
Additivation	Formulated biobased chainsaw oil	BCO	+35	+18	+122	+6	+60	−2	−1	−1
	Formulated mineral chainsaw oil	MCO	+2	+1	+43	+9	+22	+114	+22	+84
Allocation procedure for crushing	Energy-based allocation	BCO	+41	+41	+41	+41	+41	+41	+41	+41
Extraction yields in the refining stage	Different base oil production yields	MCO	−1	−2	−2	−2	−2	−2	−2	−4

BCO baseline scenario for the biobased chainsaw oil, *MCO* baseline scenario for the mineral chainsaw oil

additives that are available and by confidentiality issues (Girotti et al. 2011).

However, the contribution of additives to the life cycle impacts of lubricants can be important (Girotti et al. 2011). We reported only four studies specifying that additives were taken into account (Wightman et al. 1999a, b; Girotti et al. 2011; Raimondi et al. 2012), but only two (Girotti et al. 2011; Raimondi et al. 2012) detailed how additives were studied.

In our study, we could not get information on the specific additives used in the biobased chainsaw oil made on the farm for confidentiality reasons. Therefore, we decided to assess the influence of additives that can classically be found in the formulation of chainsaw oils. Standard chainsaw oils do not contain a large amount of additives because this kind of product is driven by cost. The average compositions of a biobased chainsaw oil and of a fossil chainsaw oil are presented in Table 9. Due to the low availability of LCI data on additives, we proceeded according to the simplified methodology described in Girotti et al. (2011) and in Raimondi et al. (2012) which allows to use ecoinvent data to obtain simplified LCA of additives. The proposed ecoinvent correspondences and assumptions for modelling additives are reported in the Electronic Supplementary Material.

The environmental impacts for the fully formulated biobased and mineral chainsaw oils are shown in Figs. 3 and 4. For both oils, the contribution of additives to the overall life cycle was not negligible. In the biobased chainsaw oil, additives represented 5.5 % in mass, but the impact could be up to 57 % to the total impact for some impact category. In the mineral chainsaw oil, additives represented 5 % in mass, but the impact could be up to 55 % to the total impact for some category.

Even if the parameter "additivation" is evaluated as "sensitive" (results are increased by more than 10 % for different impact categories for both oils), conclusions are not reversed (see Table 8).

4.5 Allocation procedure for the crushing phase of rape seeds

In this study, we used a mass-based allocation to assign the environmental burdens between rapeseed oil and rapeseed meal in order to ensure the uniform application of allocation

Table 9 Typical compositions of biobased and mineral chainsaw oils (source: personal communication from BRUGAROLAS company)

	Biobased chainsaw oil (% *w/w*)	Mineral chainsaw oil (% *w/w*)
Base oil	94.5	95
Pour point depressant	4.5	5
Antioxidant	1	–

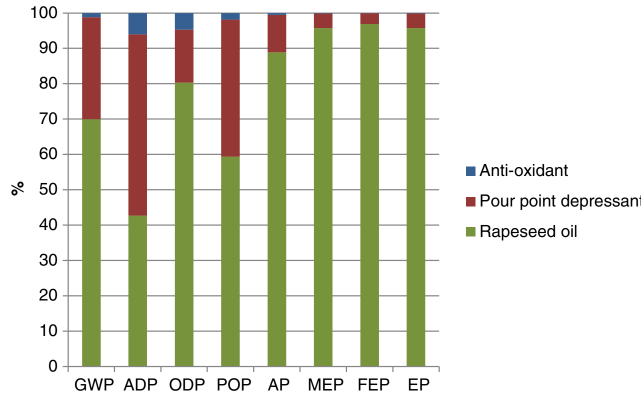

Fig. 3 Environmental impacts of the fully formulated biobased chainsaw oil

procedure between the biobased and the fossil chainsaw oil. In this sensitivity analysis, the environmental impact of the biobased chainsaw oil was re-evaluated using an energy-based allocation procedure which was considered more appropriate to reflect the difference in value between the oil and the meal. In this allocation, the energy content (lower heating value) of the oil was taken at 48 % (20.3 MJ/kg, dry basis), and the lower heating value of the meal was taken at 52 % (36 MJ/kg, dry basis).

Results are shown in Table 8. They show that, even if the parameter is evaluated as "sensitive" (results are increased by about 40 % for all impact categories), conclusions are not reversed.

4.6 Extraction yields in the refining stage

In this study, we used the base oil production yields from Fehrenbach (2005). In order to evaluate the influence of higher extraction yields resulting in a lower base oil yield, we used yields described in Mortier et al. (2010) for the following

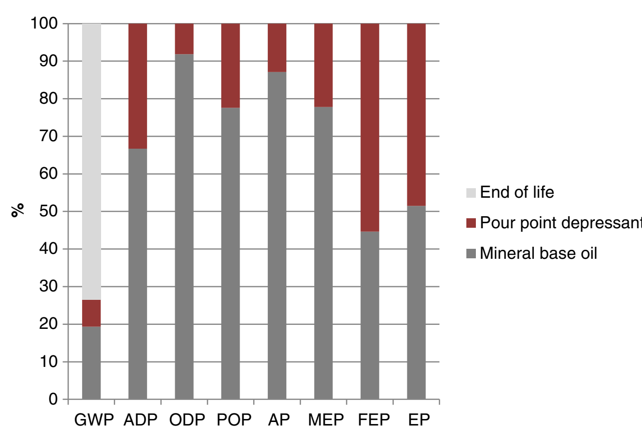

Fig. 4 Environmental impacts of the fully formulated mineral chainsaw oil

steps: deasphalting, solvent extraction, high-pressure hydrogenation, dewaxing and hydrofinishing (Electronic Supplementary Material).

Results are shown in Table 8. They show that the parameter does not have a significant influence on the results and therefore is not evaluated as "sensitive". Conclusions are logically not reversed.

4.7 Method for impact assessment

In this study, a composite method was used for impact assessment based on the recommendations issued by the International Reference Life Cycle Data System (European Commission 2011). In order to investigate the influence of the choice of the assessment method on the results, we used three different methods to re-evaluate the environmental impacts: CML 2 baseline 2000 (v2.05), ReCiPe Midpoint (H) (v1.05) and EDIP 2003 (v1.02).

Results are shown in Table 10. With CML 2 baseline 2000, conclusions are not reversed except for marine aquatic ecotoxicity for which the mineral chainsaw oil has a slightly higher impact than the biobased chainsaw oil. With ReCiPe and EDIP 2003, conclusions are not reversed.

5 Conclusions

The LCA study performed in this work indicates that for the environmental impact categories global warming potential, abiotic depletion potential, ozone depletion potential and photochemical oxidation potential, the biobased chainsaw oil made on the farm in Wallonia (without additives) has a lower impact compared to a conventional mineral chainsaw oil (without additives). On the contrary, the biobased chainsaw oil has larger acidification, aquatic eutrophication and aquatic ecotoxicity potential impacts.

As demonstrated by Raimondi et al. (2012) and Girotti et al. (2011), the contribution of additives to the overall impact of the life cycle can be high and should not be excluded from the environmental evaluation of lubricants and biolubricants. In our study, contribution of additives was not negligible for both types of oils. The conclusion regarding the comparison between the oils was not reversed when additives were taken into account notably because additives and treat rates were quite similar in both types of oils. Although evaluated, more work and more data are still needed to improve the account of additives in LCA of lubricants.

A common belief in the Walloon forest sector is that it is necessary to consume more biobased than mineral chainsaw oil to deliver the same work. Even if this belief was true for the biobased chainsaw oil made on the farm, our results show that conclusions regarding the comparison of both types of oils in terms of environmental impact would not be not reversed.

In the same way, a different allocation procedure for rapeseed oil and rape meal, a different rape seeds yield or different extraction yields in the refining stage of the mineral base oil do not change the results of the comparison between the biobased and the mineral chainsaw oil.

More widely, this study outlines the importance of agricultural practices to the overall environmental impact of biobased lubricants. For example, we observed that the substitution of only one active substance (one insecticide ingredient) could result in an important decrease of the freshwater ecotoxicity. In this sense, LCA could be very useful to improve the environmental impact of the agricultural raw materials used in the formulation of biobased lubricants. In our study, we used simplified methodologies and models to assess the final distribution and fate of pesticides or to estimate field N_2O emissions. The dataset available for the agricultural stage was not sufficient to use more complex models that allow to better estimate pesticide emission pattern on field or to take into account pedo-climatic conditions. In this perspective, improving data collection and gathering information in the agricultural sector in Wallonia would be very useful. The impact of land use change is also an issue of particular importance for biobased lubricants. Land use is connected with various environmental impacts including emissions of greenhouse gases (GHG) but also impacts on soil quality and productivity, impacts on biodiversity or impacts on water quality and availability. Today, available recommendations on how to take land use change into account exist mainly from the greenhouse gases perspective and for direct land use changes (Mattila et al. 2011). Other environmental impacts or indirect impacts are not taken into account because causal links between the use of land on the one hand, and the various environmental impacts or the indirect consequences of a change on the other hand, are not easy to define and also because there is no consensus on how to establish these links from a methodological point of view. In our study, only direct effects of land use change were considered from the GHG perspective. These effects were assumed to be null since rapeseed has been cultivated on existing farmlands for many years in Wallonia. In the future, with the expected development of biobased products, it will be important to consider these impacts.

By providing a detailed LCA on a biobased chainsaw oil, this study contributes to the development of LCA applied to biobased lubricants.

As far as mineral chainsaw oil is concerned, the setting of detailed and recent reference life cycle inventories for mineral base oils, developed in cooperation with the oil industry, is necessary. Such data would improve the application of LCA to lubricants and would make the comparison with biobased lubricants more accurate.

Table 10 Environmental impacts expressed per 1 kg of the biobased and the mineral chainsaw oils using CML 2 baseline 2000, ReCiPe and EDIP 2003 methods

	GWP (kg CO_2 eq.)	ODP (kg CFC-11 eq.)	ADP (kg Sb eq.)	FDP (kg oil eq.)	AP (kg SO_2 eq.)	AP (m^2)	POP (kg C_2H_4 eq.)	POP (kg NMVOC	POP (m^2.ppm.h)	FEP (kg $P0_4^{3-}$ eq)	FEP (kg P eq.)	MEP (kg N eq.)	EP Freshwater (CTU eq.)	EP Marine (kg 1,4 DB eq.)	EP Freshwater (kg 1,4 DB eq.)	EP Chronic (m^3)	EP Acute (m^3)
CML 2																	
Biobased chainsaw oil	0.66	4.35E−08	1.98E−03	–	9.70 E−03	–	7.34 E−05	–	–	6.17E−03	–	–	4.33E−02	130	–	–	–
Mineral chainsaw oil	3.89	1.34E−07	5.27E−03	–	8.64E−03	–	3.50E−04	–	–	4.49E−04	–	–	2.55E−02	136	–	–	–
ReCipe																	
Biobased chainsaw oil	0.66	4.08E−08	–	9.68E−02	1.37E−02	–	–	1.34E−03	–	–	7.45E−04	5.49E−03	–	4.30E−03	4.14E−02	–	–
Mineral chainsaw oil	3.89	1.54E−07	–	2.82E−01	7.51E−03	–	–	3.36E−03	–	–	2.07E−05	9.13E−04	–	1.31E−03	6.94E−04	–	–
EDIP 2003																	
Biobased chainsaw oil	0.66	4.06E08	–	–	–	0.143	–	–	2.28	–	6.56E−04	3.78E−03				2.83E03	116
Mineral chainsaw oil	3.89	1.01E−07	–	–	–	0.131	–	–	4.61	–	1.79E−05	2.06E−04	–	–	–	39.8	5.32

FDP fossil depletion potential

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